

Development of 1kWh Flywheel Energy Storage System with Superconducting Magnetic Bearing

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Abstract – Development of flywheel energy storage system using high temperature superconducting magnetic bearing is actively attempted. 1kWh flywheel was developed and we succeeded in obtaining the maximum energy storage of 1.4kWh at 20,000rpm. On the basis of this development, advanced studies about high temperature superconducting magnetic bearing has been performed. A bearing model of the large diameter of 620mm combined with the permanent magnet of Nd-Fe-B and several high temperature YBaCuO superconductors of the diameter of 150mm directly cooled by the cryogenic refrigerator were fabricated, and its performance tests were conducted. The prospect of developing 10kWh-class flywheel has been obtained on the basis of the above results. This flywheel is composed of CFRP rotor having a diameter of 1.2m, the cryogenic refrigerator and high efficient generator motor, and has the capacity of the maximum energy storage of 17kWh. We are planning to attain the development of these components and perform the verification test afterwards.

I. INTRODUCTION

A flywheel is featured by its high energy density and enabling a long working life, that is suitable for an application as an independent power supply unit, although it is rather impossible to expect such a large scale power storage as a pumped power plant.

For the conventional flywheels using mechanical bearing or normal-conducting magnetic bearing, it has been difficult to realize the high efficiency because of their larger loss. However, the development of new materials such as high temperature superconductor, CFRP and the advanced electrical technique has raised up an expectation toward high efficiency flywheel system in recent years.^[1,2]

This paper introduces the development of 1kWh unit and the evaluation test for large-scale high temperature superconducting magnetic bearing as well as summarized plan for 12.5kWh unit taking the aforesaid two results into consideration.

II. DEVELOPMENT OF 1kWh FLYWHEEL SYSTEM

The schematic drawing of 1kWh superconducting flywheel is shown in Fig.1. CFRP produced by winding the carbon filament in the circumferential direction with epoxy resin is employed because of its larger specific strength. Multi ring construction composed of three layers shown in Fig.1 is used for the purpose of decreasing the radial stress.^[3] The elasticity in three layers are reduced step by step from outside to inside.

With regard to the connection between the flywheel and the rotating shaft, a partially spherical surface supporting disk is adopted so that the supporting disk can sufficiently follow the internal displacement of the flywheel during the operation.

It is designed that the adhesive structure is used between the flywheel and the supporting disk, and the compressive stress acts on it for the whole speed range to ensure a safe operation because of disadvantage to the tensile stress. The rotor is rigidly connected to the

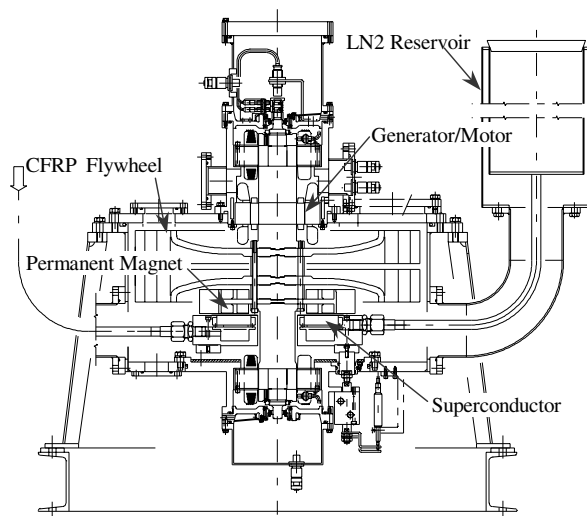


Fig.1 Schematic drawing of 1kWh flywheel with superconducting magnetic bearing

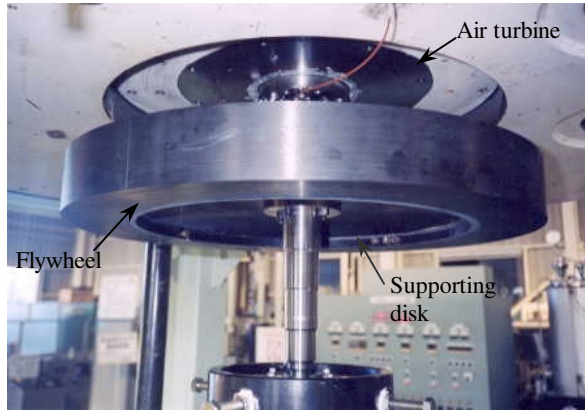


Fig.2 Spin testing facility

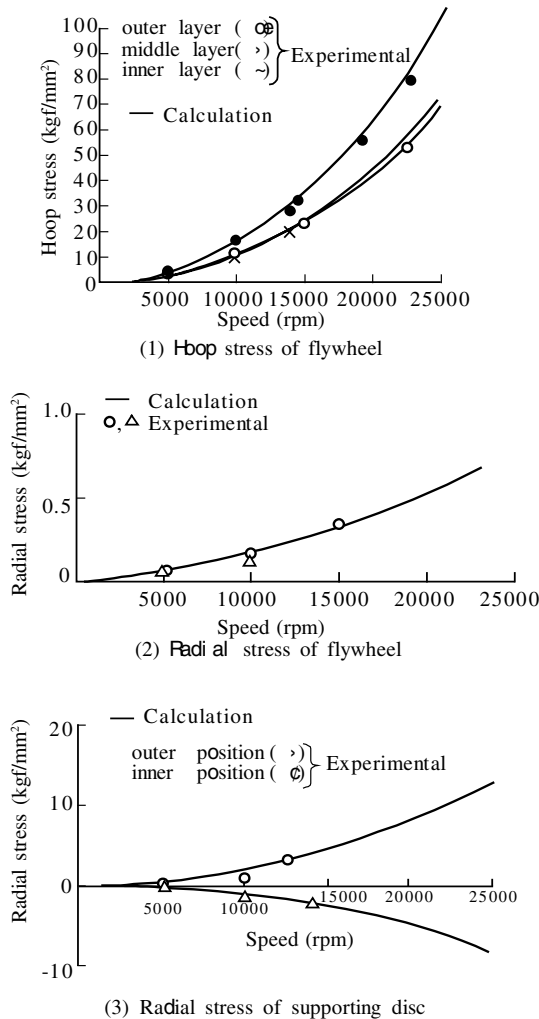


Fig.3 Spin test results for CFRP flywheel rotor

supporting disk. Two flywheels of outer diameter of 600mm, inner diameter of 450mm and the height of 70mm are used.

The inner diameter is determined on the points of decreasing the radial stress and considering the following characteristics of the supporting disk.

If the inner diameter is too large, the peripheral speed and the internal displacement of the flywheel become larger, and the supporting disk can not follow it, though the radial stress in the flywheel ring is small.

The peripheral speed of the outer diameter at 20,000rpm in this design is 628m/sec.

Prior to the final assembly with the flywheel rotor, a spin test on a single flywheel was performed to measure the stress and deformation and compare the results with the analytical values. The spin testing facility is shown in Fig.2.

The test rotor was hanged and rotated by the air driven turbine. The spin test was performed in vacuum for the purpose of decreasing the windage loss.

The instruments for this facility are a speed sensor, a radial vibration detector and strain gages for investigating the hoop and radial stresses of the flywheel ring and the radial stresses of the supporting disk. The outputs of strain gages are taken out through the slip ring.

The spin tests of the flywheel at the rotating speed of 27,000rpm have been performed, and it has been confirmed that the test rotor was able to rotate having the margin of the speed of 1.35 times to designed rotating speed of 20,000rpm. The measured stresses of CFRP flywheel ring and supporting disk reasonably coincided with the results of analysis shown in Fig.3^[4,5].

As radial stress of inner position of supporting disk is the compression and that of outer position is the tension shown in Fig.3, it is considered that the supporting disk presses the flywheel ring deforming spherically.

A vertical structure with a superconducting magnetic axial gap type bearing supporting the rotor mass of 76kg is adopted, because it is necessary to decrease the rotating loss. Its bearing load in the surface area of the permanent magnets is 0.2kgf/cm².

The permanent magnet is made of Pr-Fe-B. Its residual magnetic flux density at room temperature is 1.3T. CFRP stiffening ring with the characteristics of a light weight and high strength is adopted in order to reduce the rotating stress on the magnetic plate assembling permanent magnets. A spin test of the magnetic plate assembly was executed and its performance up to 23,000rpm has been confirmed.

High temperature superconductor is made of YBaCuO. Its current density measured in the magnetization method is 2.4×10^4 A/cm² at 77K, 0.3T.

The bearing housing containing the high temperature superconducting bulks is cooled by liquid nitrogen and lifts the rotor containing the permanent magnets. Fig.4 shows the model of high temperature superconducting magnetic bearing.

The trapezoidal high temperature superconducting bulks are arranged in a circular direction without leaving any space between them. GFRP bearing housing is used to prevent the occurrence of eddy-current losses due to the fluctuation of the magnetic field created by the rotating magnets and reduce the quantity of heat entering from outside. A lifting device is installed at the lower part of the bearing housing and adjusted the relative axial position between the rotor and the stationary parts. If a failure occurs in the superconducting magnetic bearing, the rotor moves downwards and it is supported by upper ball bearing after touching.

A floating characteristic of superconducting magnetic axial gap type bearing in the condition of zero field cooling and field cooling is shown in Fig.5, and it has been confirmed that measured bearing load reasonably coincided with the analytical values [6,7].

For layout of the rotor, two flywheels are placed opposite each other to minimize the shaft span. The upper view of the rotor is shown in Fig.6. The radial load of the flywheel is generated by the remaining mechanical unbalance and this can be reduced by an accurate assembly and a dynamic balancing. Ball bearings together with oil-squeeze film dampers which do not require complicated controls are used as radial bearings.

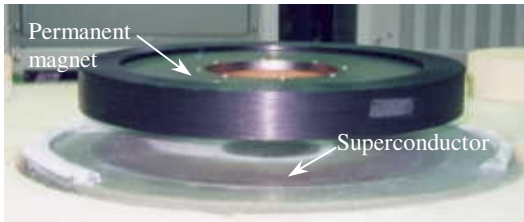


Fig.4 High temperature superconducting magnetic bearing

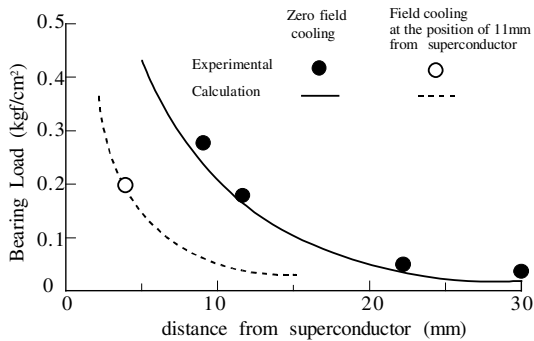


Fig.5 Floating characteristic of superconducting magnetic axial gap bearing

After several cooling down and rotational tests, the running test up to 20,000rpm was performed. It has been confirmed that the rotor rotated stably at 20,000 rpm without excessive radial vibration. The high temperature superconducting magnetic bearing was cooled on the field cooling condition at the position of 11mm from superconductor, and the axial bearing gap was set at the position of 2mm. At this time the distance from superconductor was 4mm shown in Fig.5 as the thickness of GFRP bearing housing was 2mm. This gap was constant during the above running test. And the temperatures of outer GFRP bearing housing was constant at 173K during the above running test. And also the function of the touch bearing of the upper ball bearing was confirmed.

The view of verification tests of 1kWh superconducting flywheel is shown in Fig.7.

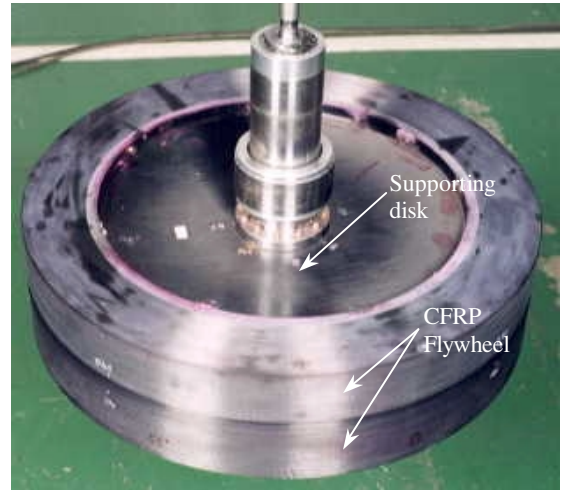


Fig.6 Upper view of the rotor

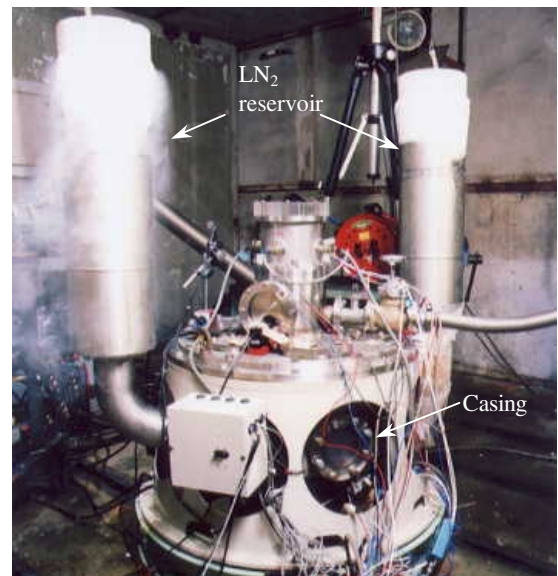


Fig.7 A view of 1kWh superconducting flywheel

III. BEARING ELEMENTAL TEST WITH CRYOGENIC REFRIGERATOR

The evaluation test for large-scale high temperature superconducting magnetic bearing was performed. The test apparatus is shown in Fig.8. The permanent magnet assembly is outer diameter of 620mm and inner diameter of 320mm and is composed of four rings whose poles to the superconductors are arranged to the radial direction alternately. The permanent magnet is made of Nd-Fe-B and is separated to the circumferential direction. Distributions of axial magnetic field to radial direction are shown in Fig.9.

Ten pieces of high temperature superconductors of the diameter of 150mm are arranged at equivalent intervals to the circumferential direction, and directly cooled by the cryogenic refrigerator.^[8]

The superconductor is made of YBaCuO and its critical current density is $3 \times 10^4 \text{ A/cm}^2$ at 77K, 0.3T by the magnetization method.

The temperature of superconductor surface is measured by thermo-couple.

The load to the axial direction is given as W , and the displacement is measured as z shown in Fig.8. Also the load to the radial direction is given as F , and the displacement is measured as r .

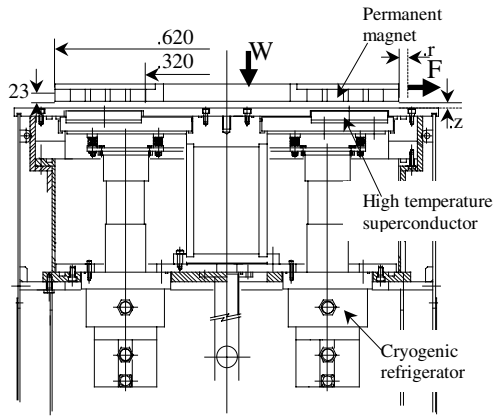


Fig.8 Bearing test apparatus

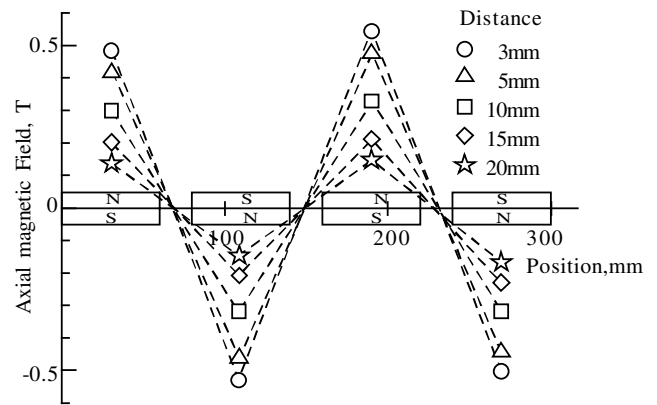


Fig.9 Distribution of axial magnetic field to radial direction

The characteristics of repulsion force to axial direction at the several positions of initial cooling are shown in Fig.10. The repulsion force in case of zero field cooling was the largest, and according to the reduction of the clearance at the initial cooling it became small.

The stiffness to radial direction at the points of A, B, C, D and E in Fig.10 were shown in Fig.11. According to the reduction of the distance from the superconductor at initial cooling, they increased. It is considered that the stiffness to radial direction increased owing to the increase of pinning force together with the increase of magnetic fluxes.

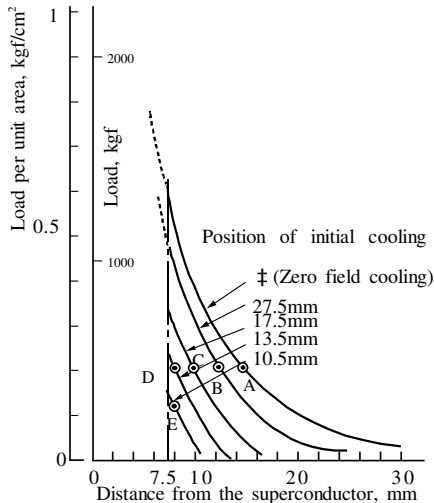


Fig.10 Characteristics of repulsion force to axial direction

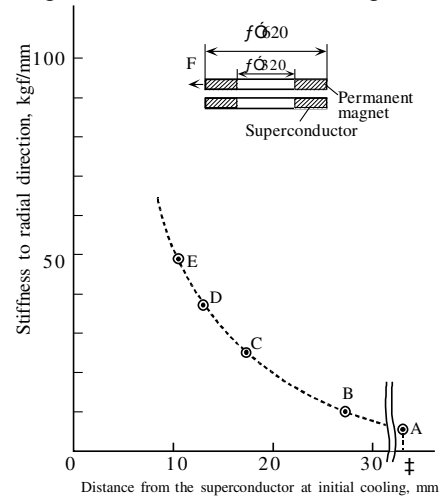


Fig.11 Characteristics of repulsion force to radial direction

Fig.12 shows the bearing characteristics of load cycling tests in case of different cooling conditions. At the cycling test of radial direction, the center of the magnet returned at the initial position in case of the field cooling, though it did not return in case of zero field cooling

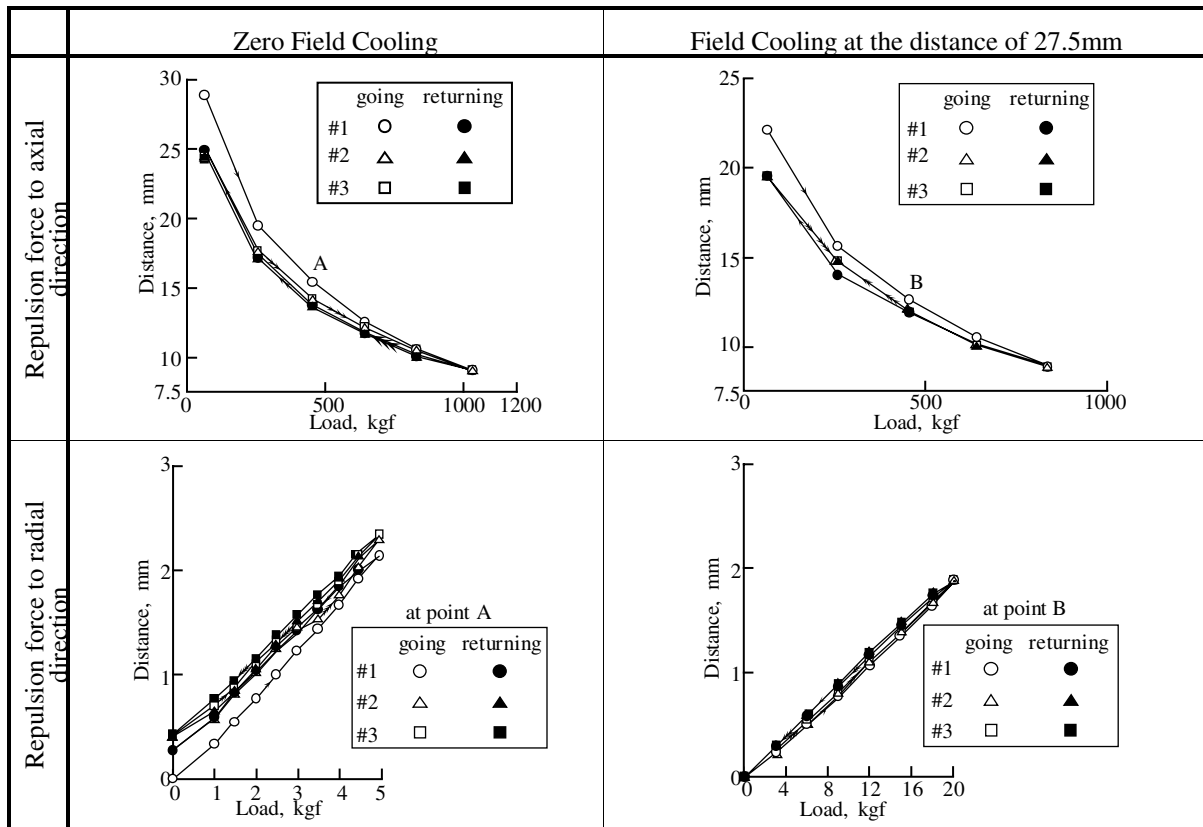


Fig.12 Bearing characteristics of load cycling tests

IV. FUNDAMENTAL DESIGN OF 12.5kWh FLYWHEEL SYSTEM

Based upon the results of prototype test for 1kWh unit and ingredient test of high temperature superconducting magnetic bearing with cryogenic refrigerator cooling, a conceptual designing for 12.5kWh unit has been conducted. Table1 indicates the specifications and Fig.13 illustrate the fundamental drawing. Now, the details are under planning.

Table1 Specification of 12.5kWh flywheel system

Item	Value
Maximum storing energy	17kWh
Discharge capacity	12.5kWh
Rotation speed	10,000-5,000rpm
Diameter of flywheel	1.2m
Bearing load	0.5kgf/cm ²

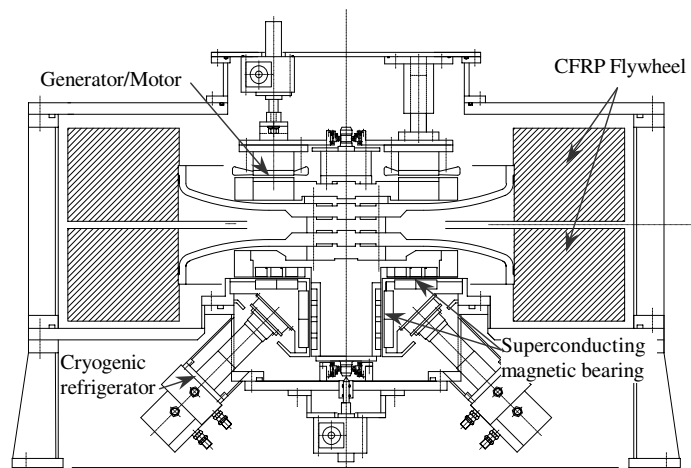


Fig.13 Fundamental drawing of 12.5kWh flywheel system

V. CONCLUSION

- (1) 1kWh CFRP flywheel with the high temperature superconducting magnetic bearing was trial manufactured and it was confirmed that the rotor rotated stably at 20,000rpm without excessive radial vibration.
- (2) The operation test by decelerating/accelerating the generator/motor was performed and the maximum energy storage 1.4kWh at a speed of 20,000rpm was attained.
- (3) A bearing model of the large diameter of 620mm for large-scale flywheel was fabricated and the required bearing load capacity of 0.5kgf/cm² was confirmed.
- (4) According to the reduction of the clearance at the initial cooling, the stiffness to the radial direction increased in spite of decreasing axial repulsive force.
- (5) At the cycling test of radial direction, the center of the permanent magnet returned at the initial position in case of field cooling, though it did not return in case of zero field cooling.
- (6) On the basis of above results the prospect of the high temperature superconducting magnetic bearing for 12.5kWh flywheel was obtained.

VI. REFERENCES

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